ANALYSIS OF DELAY FORMULAS FOR SIGNALIZED INTERSECTIONS

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ABSTRACT

The increasing number of traffic signals and traffic signal systems in urban areas is influencing traffic flow patterns on roadways. The intersections, being the focal point of conflicts and congestion in roadway network, is a critical issue in the efficient use of the urban street system. This paper aims to analyze delay formulas for signalized intersections, and to compare between the 1985 Highway Capacity Manual (HCM) delay formula, the Australian, the Canadian, and the English TRANSYT 8 delay formula. A general formula will be also represented that embraces them all.

Keywords: Transportation Management and Control, Signalized Intersections, Overall Delay, Nonrandom Delay, Overflow Delay, Green Ratio, Degree of Saturation, Capacity per Cycle, Highway Capacity Manual Delay Formula.

INTRODUCTION

Vehicle movement on congested urban streets is generally characterized by slowness, delays, and increased fuel consumption. The common goal of city planers and traffic engineers is to improve the traffic flow by making the best possible use of the existing network of streets and traffic control devices.

Intersections of streets at grade in urban regions are critical portions of road networks because they are points of considerable congestion and delay. The efficiency and capacity of the entire street system is generally dependent on the characteristics of the intersections in the system.

The time a driver has to wait before he can cross or merge with other streams is an important performance indicator for intersections. This delay used to evaluate the performance of signalized intersections.

Over the past 15 years, several formulas for calculating average delays at traffic signals have been developed. Each of these approaches tries to estimate the average delays under non-steady state traffic volumes.

This paper contains three parts. The first part analyses the important factors that affect signalized intersection performance. The second part analyses different delay formulas, compares between them, and introduces a generalized form that embraces them all. Finally, delay calculations were made for many combinations of cycle lengths, green ratios, v/c ratios to aid in identifying the relationships between the computed delay and volume capacity ratio for lane groups at signalized intersection.

FACTORS AFFECTING SIGNALIZED INTERSECTION CAPACITY

The capacity of a signalized intersection is defined as the maximum number of vehicles that can pass through an intersection during the green period under prevailing roadway, environmental, and traffic conditions. Capacity is not a constant quantity, but it depends on a number of factors, some of which are static such as:

* Intersection geometric design elements (width of approach, width of lanes, number of lanes, grade, radius of turn).

  Others of which are dynamic such as:
* Operating Conditions
  (green ratio, peak characteristics, parking situation, and bus stop operations).
* Traffic characteristics
  (traffic composition, volume capacity ratio or degree of saturation, and pedestrian activity).

  Another factors such as:

* Weather,
* Driver behavior,
* Population density in the study area,
* Roadway surface conditions, and
* Adjacent land used,

can affect the capacity of a signalized intersection.

Different formulas have been derived for the relationship between intersection geometric elements and saturation flow. Kimber and Semmens [4] found a slightly nonlinear relationship between lane width W_l and saturation flow S_l. The relationship is given by:

$$S_l = 18W^2_l - 298 * W_l + 2964 \quad \text{pch}$$

Webster [9] investigated the relationship between saturation flow and turning radius:

$$S = 1800 * (1 + 5/R)$$

Branston [3] found differences in saturation flows between peak and off-peak periods:

$$S = 885 + 68\ W \quad \text{off-peak}$$
$$S = 1045 + 68\ W \quad \text{peak}$$

where:
W :Lane width in feet,
S :Saturation flow in passenger car/hr

Webster and Cobbe [9] reported that the reduction in saturation flow caused by a parked car near the stop line on a particular approach is equivalent to a loss of roadway width at the stop line. For a parked car at 10 meter from the stop line, a loss of roadway width of 10 cm can be considered (for a green period of 72 seconds).

Trucks, buses, and turning vehicles have a greater flow impedance effect than do straight- through passenger cars. The effect of flow impedance of these vehicles are generally accounted by equating them to an equivalent number of through-car units.

Finally, unfavorable weather condition and poor visibility cause reductions in speed and generally have an adverse effect on the intersection capacity.

VEHICLE DELAYS AT SIGNALIZED INTERSECTION

The average delay per vehicle, d, to vehicles arriving in a specified flow period at traffic signals can be expressed as the sum of two delay terms:

$$d = d_1 + d_2$$

where:
d_1: nonrandom (uniform) delay term,
d_2: overflow delay term

The nonrandom delay is the delay due to signal cycle effects. Its calculation assumed that the number of vehicles that arrive during each signal cycle is fixed and equivalent to the average flow rate per cycle.

The overflow delay term represents the additional delay experienced by vehicles arrive time and its discharge in different cycles. This delay component results from temporary oversaturation due to the random nature of arrivals and due to the persistent oversaturation when the volume capacity ratio exceeds than 1.

The Highway Capacity Manual method [7], HCM, estimates the nonrandom delay for each lane group from the following relationship:

$$d_1 = 0.38 * C * (1-u)^2 / (1 -u*X)$$

where:
d_1: nonrandom stopped delay for vehicle in second/vehicle
C: Cycle length in sec.
u: green ratio, g/C
X: degree of saturation (volume capacity ratio).

The Australian [2], Canadian [6], and TRANSYT 8 [8] methods expressed the nonrandom delay component as:

$$d_1 = 0.5 * C * (1-u)^2 / (1 -u*X)$$

where:
d_1: nonrandom overall delay for vehicle in second/vehicle.

The HCM nonrandom delay formula differs from the Australian, Canadian, and the English formulas because a factor of 1/1.3 is applied to convert the overall delay to stopped delay, since the HCM formula gives a stopped delay, whereas the other formulas give overall delay (It is assumed that the stopped delay is 77% the overall delay).

The HCM estimates the overflow delay component for each lane group from the following relationship:

$$d_2 = 173 * X^2 [(X-1) + \sqrt{(X-1)^2 + 16X/c}]$$

where:
c: capacity in Vehicles/hour

The Australian method considered the factor X_o, which defined as the degree of saturation below which the overflow queue is zero, and expressed the overflow delay component as:

$$d_2 = 900 * T [(X-1) + \sqrt{(X-1)^2 + 12(X-X_o)/(c*T)}]$$

$$X_o = a + b * S * g$$

where:
T: Flow period in hours
a, b: Constants, a=0.67, b=1/600
S*g: Capacity per cycle
S: Saturation flow in Veh./hr.
g: effective green time in seconds.

Both the Canadian and English methods did not consider the factor Xo. They estimate the overflow delay component as:

Canadian:

$$d_2 = 900 * T [(X - 1) \sqrt{(X-1)^2 + 4X/(c*T)}]$$

TRANSYT 8:

$$d_2 = (900 * T / X) * [(X - 1) \sqrt{(X-1)^2 + 4X/(c*T)}]$$

The HCM model differs from the other three models with the X^2 factor, whereas the Australian model differs from the other models with a nonzero X_o parameter. The flow period T is fixed in the HCM (T = 0.25 hr). Again a factor of 0.77 is applied to convert the overall delay to stopped delay.

Putting T=0.25, the HCM, Australian, Canadian, and TRANSYT 8 models can be generalized as the following formula:

$$d_2 = (225 * X^n) * [(X - 1) \sqrt{(X-1)^2 + 4m/(X-X_o)/c}]$$

$$d_1 = 0.5 * C * (1-u)^2 / (1 -u*X)$$

$$X_o = a + b * S * g$$

The values of the calibration parameter n, m, a, and b for the HCM, Australian, Canadian, and English models are given in Table (1).

Table 1. Values of parameters in the HCM, Australian, Canadian, and TRANSYT 8.

	n	m	a	b
HCM	2	4	0	0
Australian	0	12	0.67	1/600
Canadian	0	4	0	0
TRANSYT 8	-1	4	0	0

ANALYSIS

Overall delay calculation were made for many combinations of cycle lengths, ratio of effective green time to cycle length (g/C ratio) to aid in identifying the relationships between computed delay and volume capacity ratio (v/c) for lane groups at signalized intersections.

It is appear from Figures (1), and (2) that short cycle lengths and high g/C ratios are associated with low delays, even at high v/c ratios. These Figures also indicate that, conversely, some long cycle lengths and low g/C ratios lead to high delays. The degree of saturation has little influence on overall delays at v/c levels below 0.6. Overall delays increases rapidly at levels above this ratio. Delays at v/c values of 1.2 are much higher than delay at v/c of 1.0.

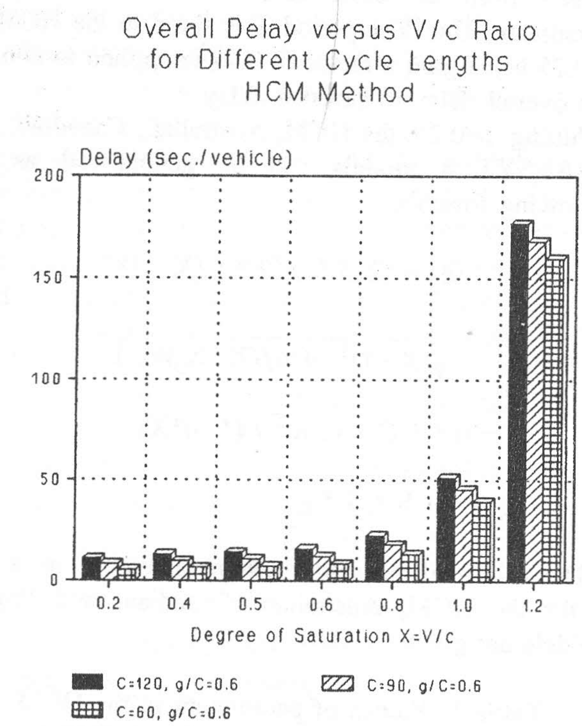


Figure 1: Overall Delay versus v/c ratio for Different Cycle Lengths, HCM

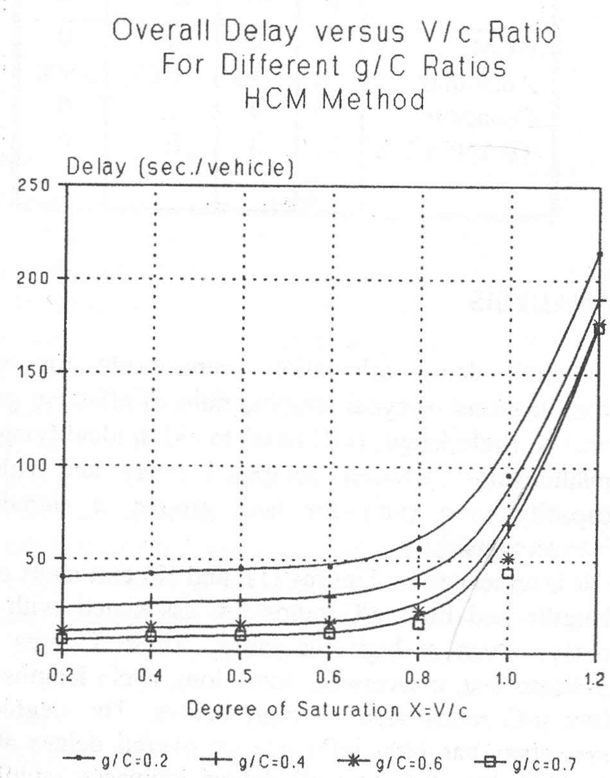


Figure 2: Overall Delay versus v/c ratio for Different g/C ratios, HCM

Analysis of the nonrandom delay (d_1), and overflow delay (d_2) component (Figure 3, and 4), show that only d_1 is affected by the variation of the cycle length.

Figure (5) illustrates a comparison for the calculated overall delays by HCM, Australian, Canadian, and TRANSYT 8 models. This Figure shows that, for v/c > 1.0 (oversaturated intersections) the HCM overestimates the delays. The overflow delay component in the HCM method (Figure 6) for v/c > 1.0 is relatively high, therefore it is recommended to use its formula with a caution for values of X up to 1.2, the values higher than 1.2 are not recommended.

The Australian method considers the factor X_o, which is defined as the degree of saturation below which, the overflow delay is zero. Applying this model for X < 0.8 gives d_2 negative. This means that, according to the Australian method, the additional overflow delay appears only at a certain degree of saturation, namely, at $X \geq 0.8$.

The HCM defines the level of service (LOS) for signalized intersections in terms of delay. Table (2) shows the level of service criteria for signalized intersections according to HCM.

Table 2. Level of Service Criteria for Signalized Intersection [7]

Level Of Service	Delay (Sec./Vehicle)
A	< 5.0
B	5.1 to 15.0
C	15.1 to 25.0
D	25.1 to 40.0
E	40.1 to 60.0
F	> 60.0

Figure (7) presents these criteria for the HCM, Australian, Canadian, and TRANSYT 8 models. This Figure shows that, for a signalized intersections operated with v/c from 0.4 to 0.6, the four models result different LOS for the same intersection condition. The HCM, Canadian, and TRANSYT 8 result delays with LOS C and B (for cycle lengths 120, 90, 60, and g/C = 0.6), whereas, the delays calculated by the Australian equation give LOS B. For oversaturated signalized intersections ($X \geq 1$), all models calculation represents a different delay values but with the same LOS, namely F. For a degree of saturation of 0.8, HCM and Australian methods result the same LOS (C and B), whereas the other two models give LOS D, and C.

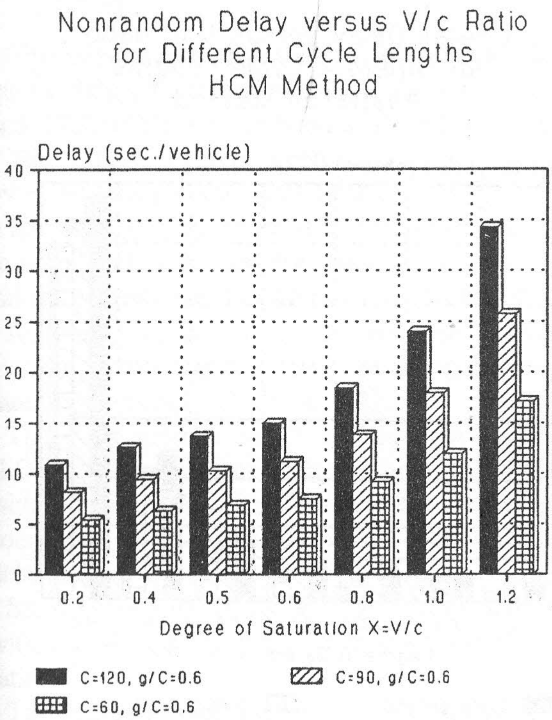
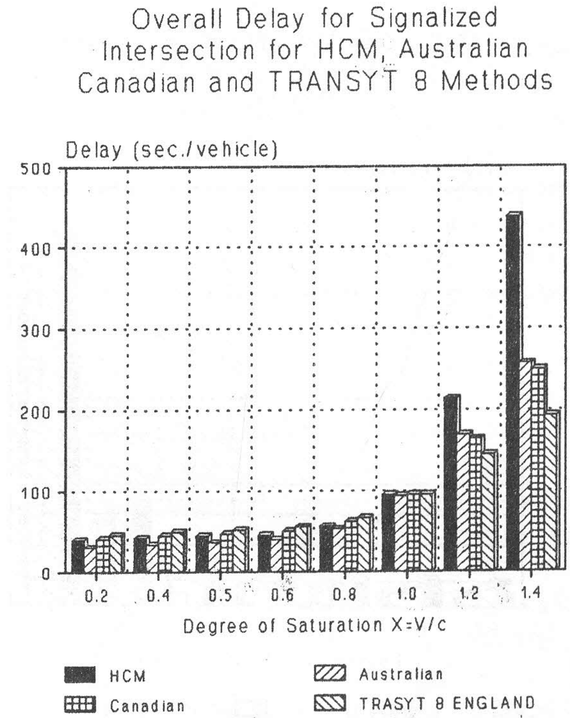


Figure 3: Nonrandom Delay versus v/c ratio for Different cycle lengths, HCM



C=120,g/C=0.2 Figure 5: Comparison between calculated Overall Delays by four Methods

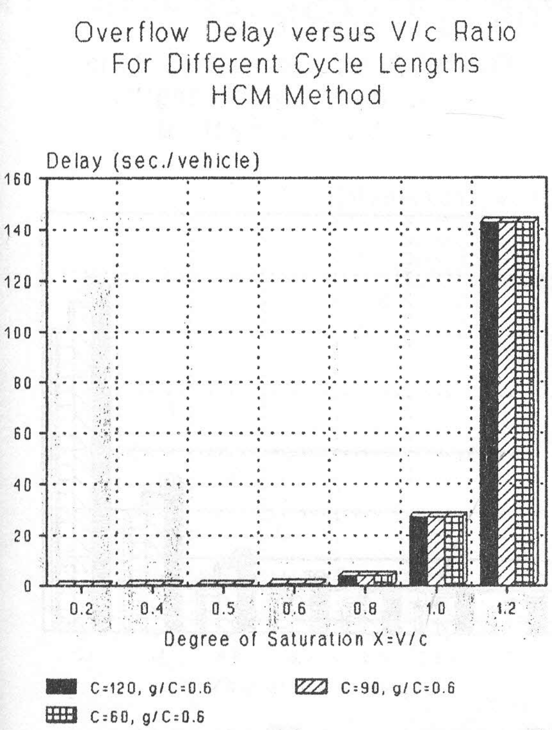
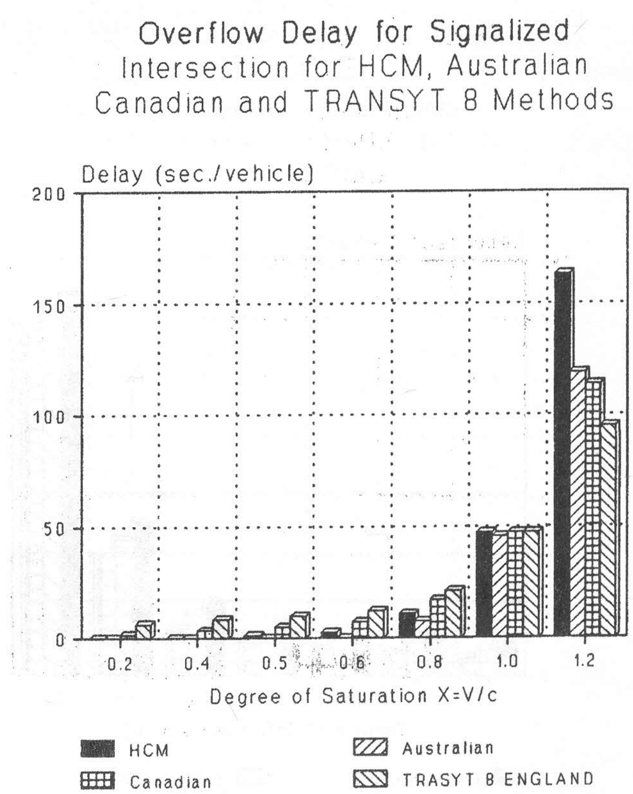
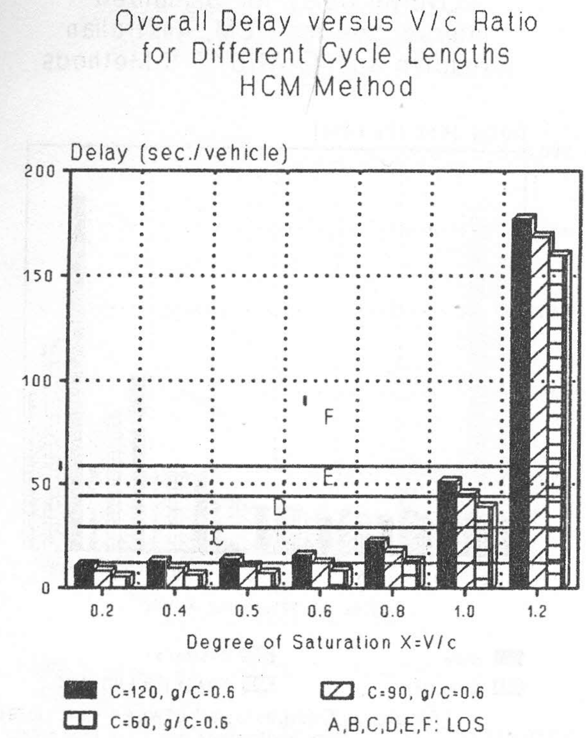


Figure 4: Overflow Delay versus v/c ratio for Different Cycle Lengths, HCM



C=120,g/C=0.2 Figure 6: Comparison between caculated Overflow Delays by four Methods



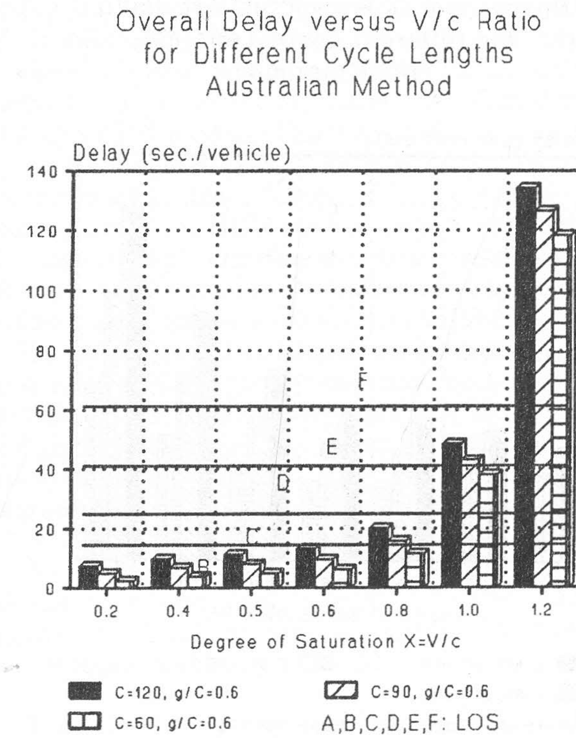
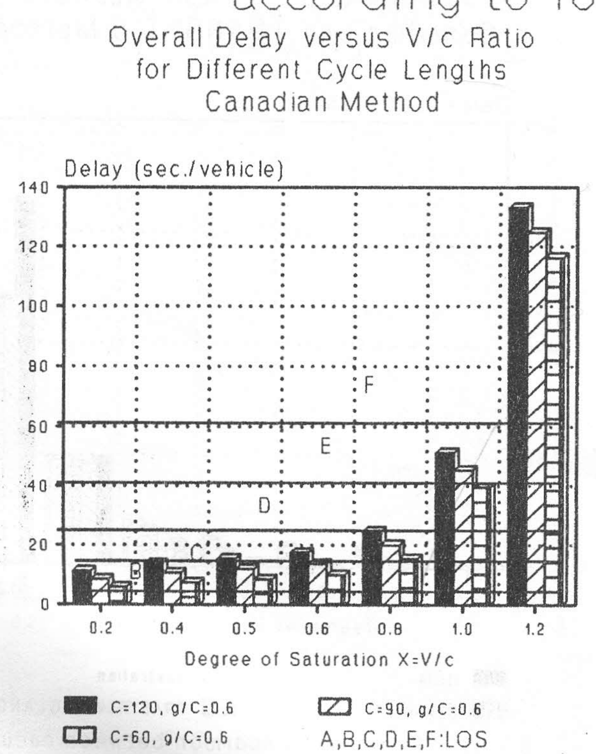
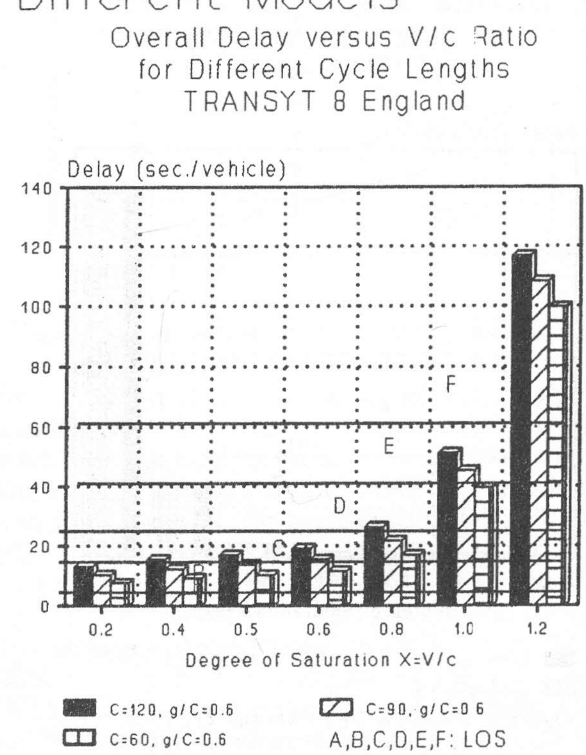


Figure 7: Level of Service for Signalized Intersection according to four Different Models





CONCLUSIONS

This paper has analyzed delay formulas for signalized intersections. Four models, HCM, Australian, Canadian, and TRANSYT 8 have been analyzed and compared.

The HCM method overestimate the delays. The overflow delay component in the HCM for $v/c > 1.0$ is relatively high, therefore it is recommended to use its formula with a caution for values of v/c up to 1.2, the values higher than 1.2 are not recommended.

According to the Australian method, the additional overflow delay appear only at a certain degree of saturation, namely at $v/c \geq 0.8$.

The four models result different level of service (LOS) for intersections with the same traffic conditions with v/c from 0.4 to 0.6. Whereas for the oversaturated conditions ($v/c \geq 1.0$), all models represent a different delay values but with the same LOS.

Short cycle lengths and high g/C ratios are associated with low delays for the four models, even at high v/c ratios.

The degree of saturation has little influence on overall delays at v/c levels below 0.6. Overall delays increases rapidly at levels above this ratio. Delays at v/c values of 1.2 are much higher than delay at v/c of 1.0.

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